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AD-A244 815



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Office of Navy Research
Scientific Officer
Attn: Dr. A. K. Vasudevan, Code 1216
Contract No. N00014-91-C-0124
Item No. 0002, Sequence No. A001
800 N. Quincy Street
Arlington, Va 22217-5000

Subject: Submittal of the Progress Report, FR21998-2

Gentlemen:

In accordance with the applicable requirements of the contract, we herewith submit one (1) copy of the subject report.

Very truly yours,

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney

Margaret B Hall

Margaret B. Hall
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FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS

Technical Progress Report

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15 December, 1991

Period of performance
16 September 1991 through 15 December 1991

Contract N00014-91-C-0124

Prepared for:
Dr. A. K. Vasudevan, Scientific Officer



Office of Naval Research
Department of the Navy
800 N. Quincy Street
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Statement A per telecon Dr. A K Vasudevan
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NWW 1/8/92

I. Introduction and Program Objective

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences it is helpful to review the evolution of high temperature airfoils.

Characteristics of Single Crystal Materials

Modern gas turbine flight propulsion systems employ single crystal materials for turbine airfoil applications because of their superior performance in resisting creep, oxidation, and thermal mechanical fatigue (TMF). These properties have been achieved by composition and alloying, of course, but also by appropriate crystal orientation and associated anisotropy.

Early aeroengine turbine blade and vane materials were conventionally cast, equiaxed alloys, such as IN100 and Rene'80. This changed in the late 1960s with the introduction of directionally-solidified (DS) MAR-M200 + Hf airfoils. The DS process produces a $\langle 001 \rangle$ crystallographic orientation, which in superalloys exhibits excellent strain controlled fatigue resistance due to its low elastic modulus. The absence of transverse grain boundaries, a 60% reduction in longitudinal modulus compared with equiaxed grains, and its corresponding improved resistance to thermal fatigue and creep, permitted significant increases in allowable metal temperatures and blade stresses. Still further progress was achieved in the mid-1970s with the development of single crystal airfoils¹.

The first such material, PWA 1480, has a considerably simpler composition than preceding cast nickel blade alloys because, in the absence of grain boundaries, no grain boundary strengthening elements are required. Deleting these grain boundary strengtheners, which are also melting point depressants, increased the incipient melt temperature. This, in turn, allowed nearly complete γ' solutioning during heat treatment and thus a reduction in dendritic segregation. The absence of grain boundaries, the opportunity for full solution heat treatment, and the minimal post-heat treat dendritic segregation, result in significantly improved properties as compared with conventionally cast or directionally solidified alloys. Single crystal castings also share with DS alloys the $\langle 001 \rangle$ crystal orientation, along with the benefits of the resulting low modulus in the longitudinal direction.

Pratt & Whitney has developed numerous single crystal materials. Like most, PWA 1480 and PWA 1484 are γ' strengthened cast mono grain nickel superalloys based on the Ni-Cr-Al system. The bulk of the microstructure consists of approximately 60% by volume of cuboidal γ' precipitates in a γ matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered Cubic (FCC) nickel aluminide compound. The macrostructure of these materials

¹ Gell, M., D. N. Duhl, and A. F. Giamei, 1980, "The Development of Single Crystal Superalloy Turbine Blades," *Superalloys 1980*, proceedings of the Fourth International Symposium on Superalloys, American Society for Metals, Metals Park, Ohio, pp. 205-214.

is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in $\langle 001 \rangle$ type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstructural discontinuities, and often exert a controlling influence on the fatigue initiation behavior of the alloy. Also, since the eutectics are structurally dissimilar from the surrounding matrix their fracture characteristics will differ.

Single Crystal Fatigue

The fatigue process in single crystal airfoil materials is a remarkably complex and interesting process. In cast single crystal nickel alloys, two basic fracture modes, crystallographic and non-crystallographic, are seen in combination. They occur in varying proportions depending upon temperature and stress state. Crystallographic orientation with respect to applied load also affects the proportion of each and influences the specific crystallographic planes and slip directions involved. Mixed mode fracture is observed under monotonic as well as cyclic conditions.

Single crystal turbine blades are cast such that the radial axis of the component is essentially coincident with the $\langle 001 \rangle$ crystallographic direction which is the direction of solidification. Crystallographic fracture is usually seen as either octahedral along multiple (111) planes or under certain circumstances as (001) cleavage along cubic planes.

Non-crystallographic fracture is also observed. Low temperatures favor crystallographic fracture. At higher temperatures, in the 427C range, small amounts of non-crystallographic propagation have the appearance of transgranular fatigue in a related fine grain equiaxed alloy. Under some conditions, this propagation changes almost immediately to the highly crystallographic mode along (111) shear planes, frequently exhibiting prominent striations emanating from the fatigue origin and continuing to failure in overstress. Under other conditions the non-crystallographic behavior can continue until tensile failure occurs. At intermediate temperatures (around 760C) non-crystallographic propagation is more pronounced and may continue until tensile overload along (111) planes occurs, or may transition to subcritical crystallographic propagation. At 982C, propagation is almost entirely noncrystallographic, similar to transgranular propagation in a polycrystal.

Damage Catalogue

This program will identify and compile descriptions of the fracture morphologies observed in SC airfoil materials under various combinations of temperature and stress associated with advanced Navy aeropropulsion systems. We will suggest fatigue mechanisms for these morphologies and catalogue them as unique damage *states*. Most testing will be accomplished under ancillary funding, and therefore be available to this effort at not cost. The work is organized into four tasks, which are described in the following paragraphs.

II. Program Organization

The program is structured into four tasks, three technical and one reporting. The individual tasks are outlined here.

Task 100 - Micromechanical Characterization

This task will define the mechanisms of damage accumulation for the various types of fracture observed in single crystal alloys. These fracture characteristics will be used to establish a series of Damage States which represent the fatigue damage process. The basis for this investigation will be detailed fractographic assessment of failed laboratory specimens generated in concurrent programs. Emphasis will be on specifically identifying the micromechanical damage mechanisms, relating them to a damage state, and determining the conditions required to transition to an alternate state.

Task 200 - Analytical Parameter Development

This task will extend current methods of fatigue and fracture mechanics analysis to account for microstructural complexities inherent in single crystal alloys. This will be accomplished through the development of flexible correlative parameters which can be used to evaluate the crack growth characteristics of a particular damage state. The proposed analyses will consider the finite element and the hybrid Surface-Integral and Finite Element (SAFE) methods to describe the micromechanics of crack propagation.

Task 300 - Probabilistic Modeling

This task will model the accumulation of fatigue damage in single crystal alloys as a Markov process. The probabilities of damage progressing between the damage states defined in Task 100 will be evaluated for input into the Markov model. The relationship between these transition probabilities and fatigue life will then be exploited to establish a model with comprehensive life predictive capabilities.

Task 400 - Reporting

Running concurrently with the analytical portions of the program, this task will inform the Navy Program Manager and Contracting Officer of the technical and fiscal status of the program through R&D status reports.

III. Technical Progress

During this reporting period, our efforts have been concentrated in identifying and characterizing numerous damage states in both PWA 1480 and PWA 1484 + HIP. Our approach builds on accepted micro mechanisms and dislocation dynamics for the deformation process in two phase FCC systems and at times will propose new hypotheses on the sequential nature of the accumulation and dissipation of energy. Sources for this study include specimen fractures and test data produced under past and present NASA, Air Force and P&W IR&D programs.

This effort pays particular attention to energy dependant fracture mode transition indicators. The transitions may be considered as bridging sequential damage states (or sub states), which may under a particular set of circumstances or conditions lead to an absorbing state such as failure. These indicators are in the form of condition (temperature or stress intensity for example) dependant fracture details on the γ' precipitate level. Further, these fracture modes are phase specific in some cases.

The eutectic phase exhibits an energy dependant sequence of fracture characteristics identical to that of the bulk microstructure but at a lower energy input level. This causes it to become a preferential fatigue crack initiation site under certain circumstances.

To date we have documented the stress intensity / temperature dependency of fracture mode transitions at room temperature, 800F and 1100F in K -gradient tests. These transitions repeat in reverse order upon subsequent constant load cycling. In addition, we have identified environment (hydrogen) dependant mode changes similar to those seen in air threshold behavior at room temperature.

We are also developing and employing advanced techniques for the analysis and characterization of fracture surfaces. This work is being carried out from the macro level to 10,000 X via optical and conventional SEM.

By the adaptation of the Philips CM-20 scanning/transmission electron microscope (STEM) for use as a fracture analyses tool, images in excess of 50,000 X are being produced. Magnifications in this range are necessary in resolving the micro-mechanisms of fracture on the γ - γ' interface level.

Graphic representations of particular fracture modes are being assembled via Unigraphics Shaded-Solid Modeling. The models are three dimensional and can be rotated to provide needed views of a particular fracture. They aid in the process of understanding and describing crack tip / microstructure interactions.

A further development has identified an automated method of obtaining both graphic and statistical assessments of micro mechanical transition indicators. The Rodenstock Laser Imaging Profilometer is intended to assess optically surface roughness via a laser stylus. For the purposes of this program, the instrument represents a scanning laser micro analyzer with statistical analysis capabilities. This provides us with a way to obtain quickly a mathematical "signature of a particular fracture mode or transition and of assessing the stochastic component of a K -dependant transition.

Representative examples of one such fracture mode transition and the methods of analysis we have described are provided in the following figures.

A PWA 1480 CT specimen was recently examined via the Laser Stylus Imaging Profilometer. The device was employed to characterize the transition region between local octahedral (Paris region) and $<001>$ planar fracture (threshold behavior). The PWA 1480 room temperature threshold crack growth evaluation was conducted in a decreasing- K mode (negative K -gradient). A fracture mode transition occurred at approximately 5 ksi *rootin*. accompanied by a marked change in growth behavior. A plot of the test results is shown in Figure 1. The

mode change is shown schematically in Figures 2 and 3. The transition was from local octahedral, (111) crystallographic fracture on the level of the cuboidal γ' precipitate, to decohesion at the γ - γ' interface upon entering the threshold region. The transition is from local octahedral to decohesion and has also been identified as the mode transition responsible for more than a 10 X increase in crack growth rate under conditions of hydrogen embrittlement. Comparative fracture surfaces for the two modes are shown in Figure 4. Details of a decohesion failure in PWA 1484 are shown in Figure 5. The transition zone for this type of fracture sequence is displayed in a 3 axis profile plot in Figure 6. The data from the profile plot has been converted to a topographical contour plot in Figure 7.

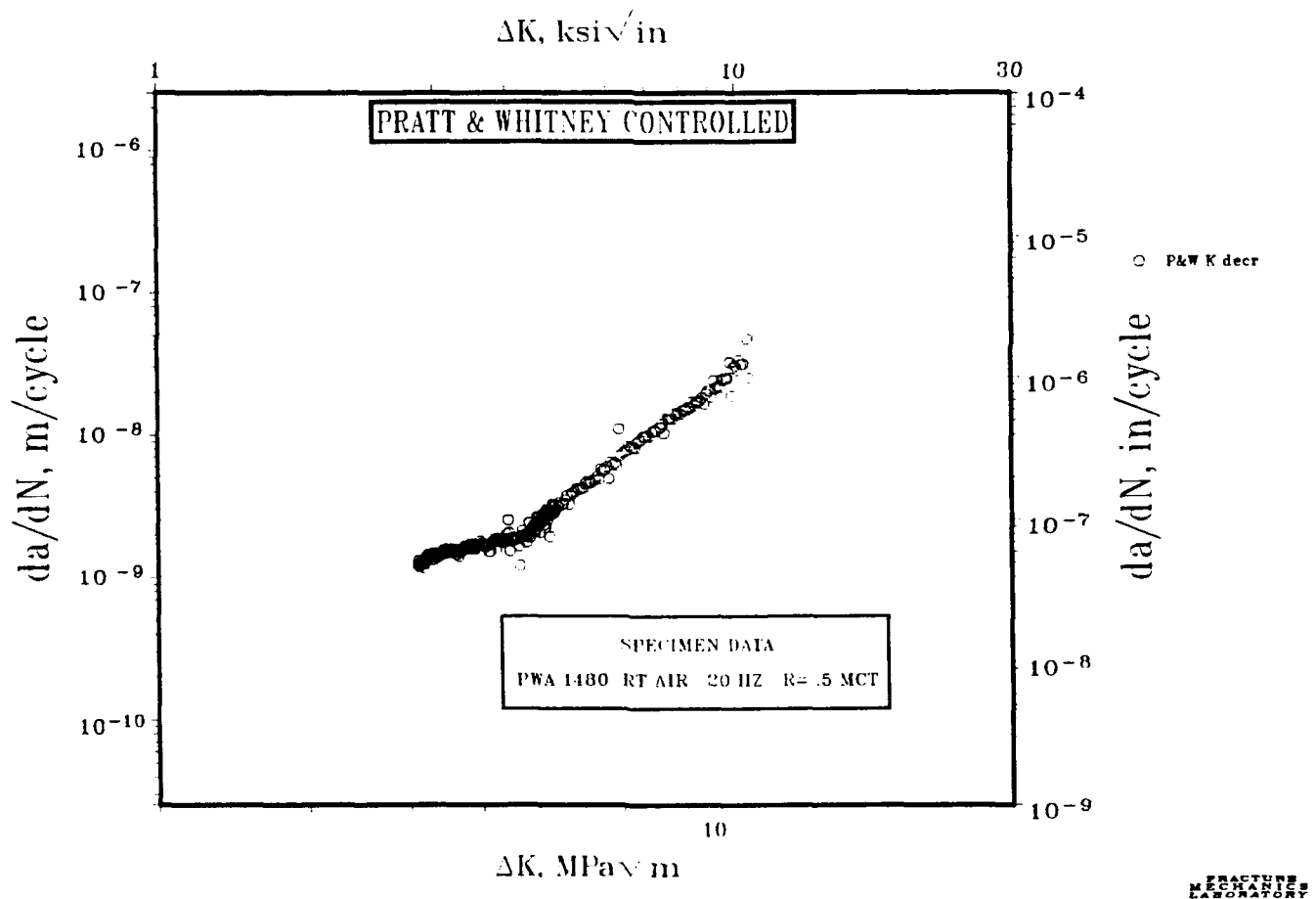


Figure 1. Discontinuity in near threshold fatigue crack growth behavior at 4-6 ksi *rootin*. for PWA 1480 at room temperature. A transition in the operative fatigue crack growth mode resulted in this behavior.

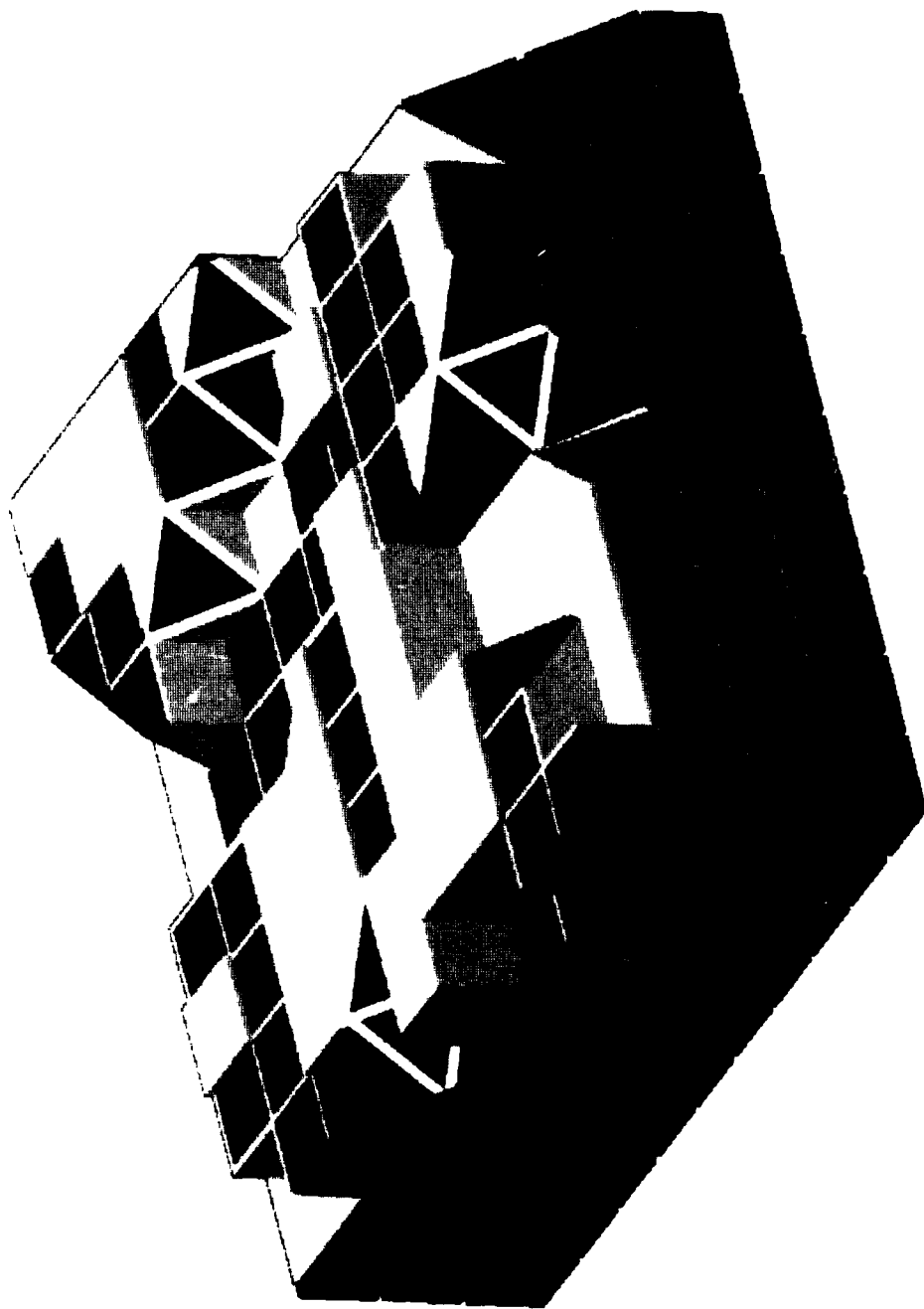


Figure 2. Shaded-solid model of fracture mode in transition region shown in previous figure. The cuboidal γ' precipitates are approximately 0.5 - 1.0 microns square, the γ matrix is approximately 0.03 microns wide.

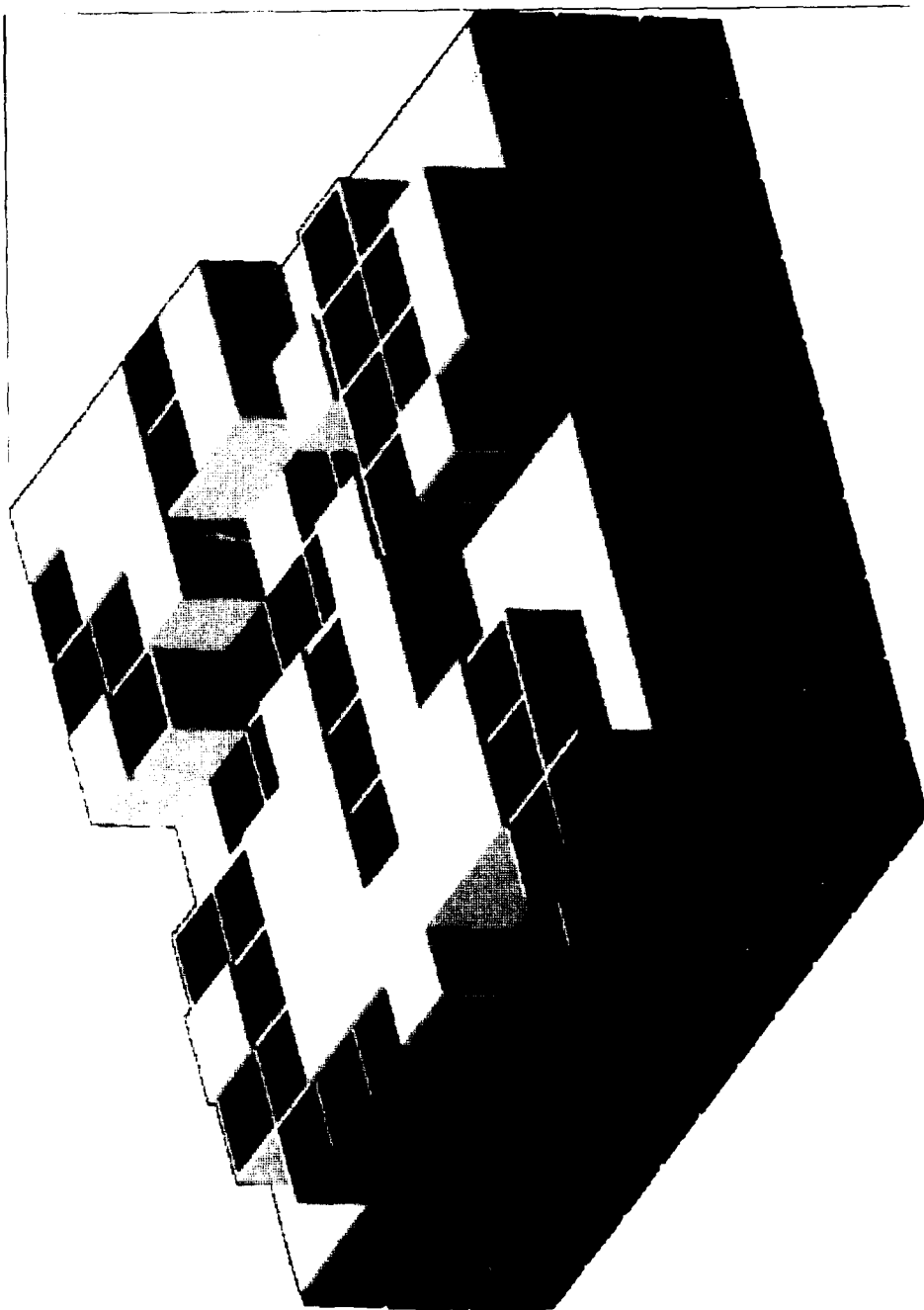
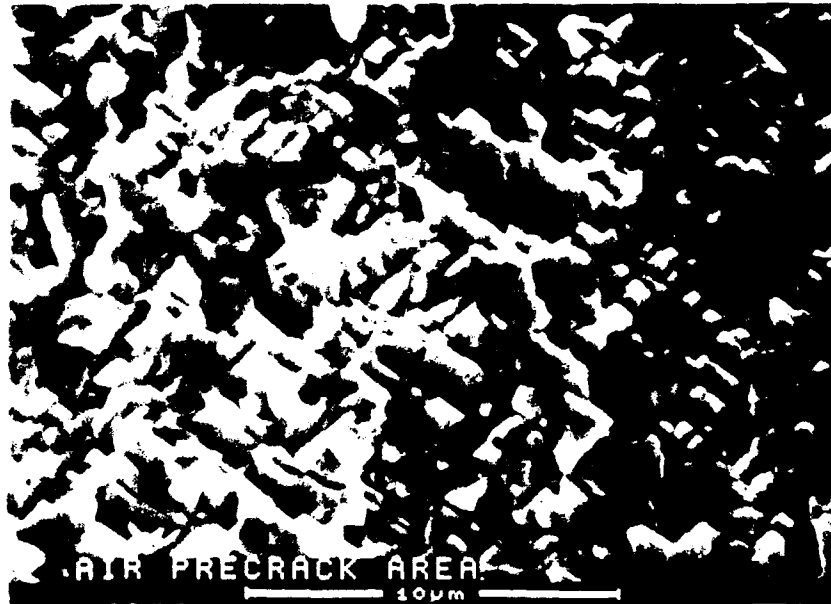
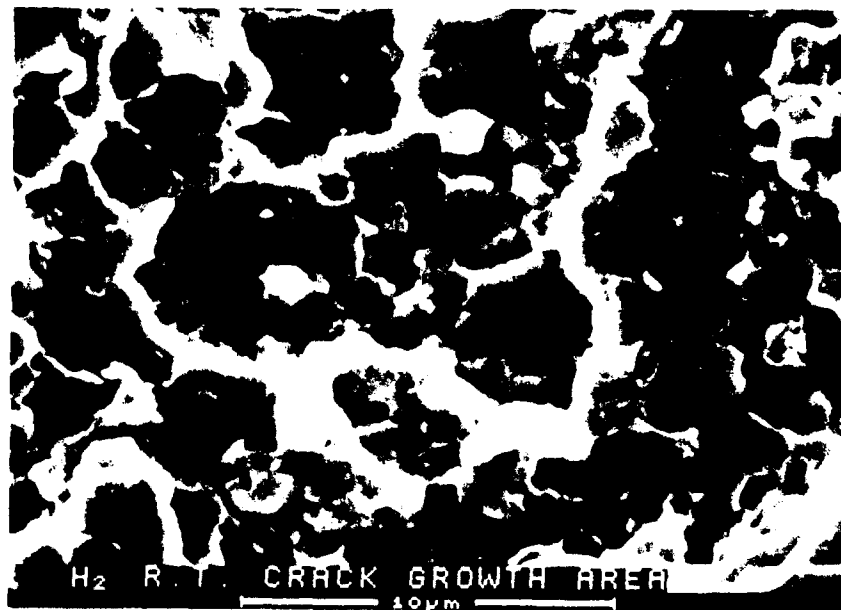


Figure 3. Model describing $y-y'$ decohesion or inter-phase fracture common to both room temperature threshold behavior in air and Paris region fatigue growth in a high pressure hydrogen environment.



*AIR-CUBOIDAL GAMMA PRIME
FRACTURED ON(111) PLANES*

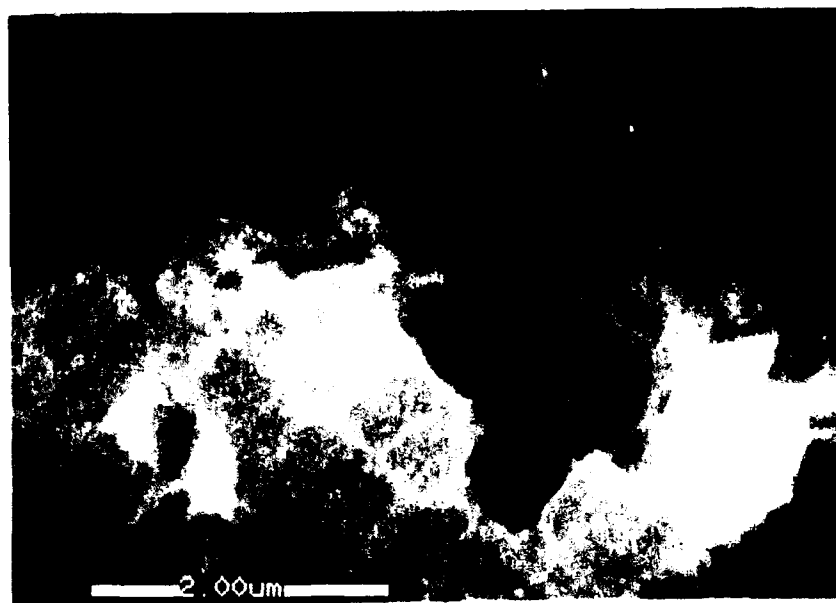


*5000 PSI GH₂ - LAYERS OF GAMMA
PRIME SEPARATED AT GAMMA MATRIX*

Figure 4. A comparison of local octahedral and γ/γ' phase decohesion (inter phase fracture). Local octahedral fracture characterizes room temperature Paris region fatigue crack growth. Inter-phase fracture is common to both room temperature threshold behavior in air and Paris region fatigue growth in a high pressure hydrogen environment.



A



B

Figure 5. Inter-phase fracture in PWA 1481 from a fatigue test in 5000 psi gaseous hydrogen simulating a rocket environment. The fracture is imaged in secondary emission in (A) for topographical contrast and suggests ductile fracture of the γ matrix surrounding the cubic precipitates. The backscattered electron image in (B) delineates the areas of the γ matrix on the fracture surface.

RODENSTOCK METROLOGY RM600

Display	
Points	7158
Scans	50
Display range5000 mil
Measurement range	30 μm
Table speed	0.079 in/min
Y Length	0.020 in
X Length	0.004 in
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Remarks	rear scan
Examiner	STETSON
Date	13.12.91

Version: 2.50E02

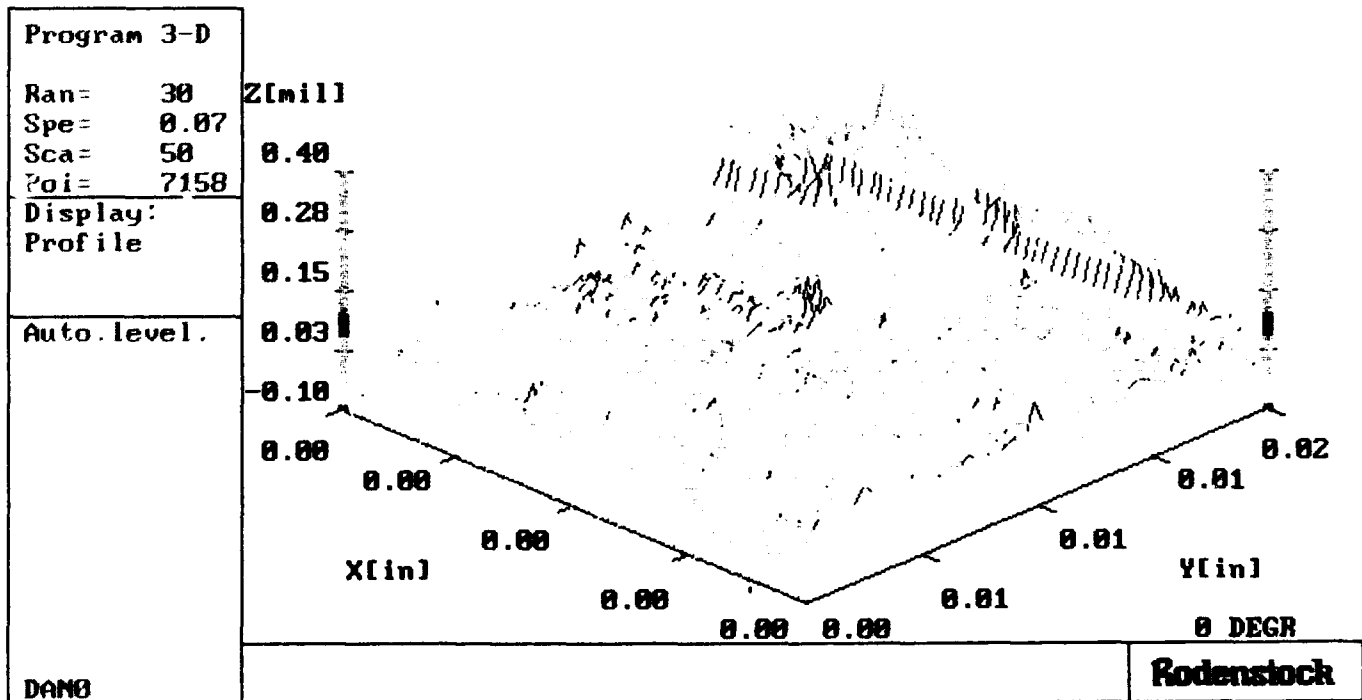


Figure 6. Profile image of transition zone from decohesion to local octahedral fracture.

RODENSTOCK METROLOGY RM600

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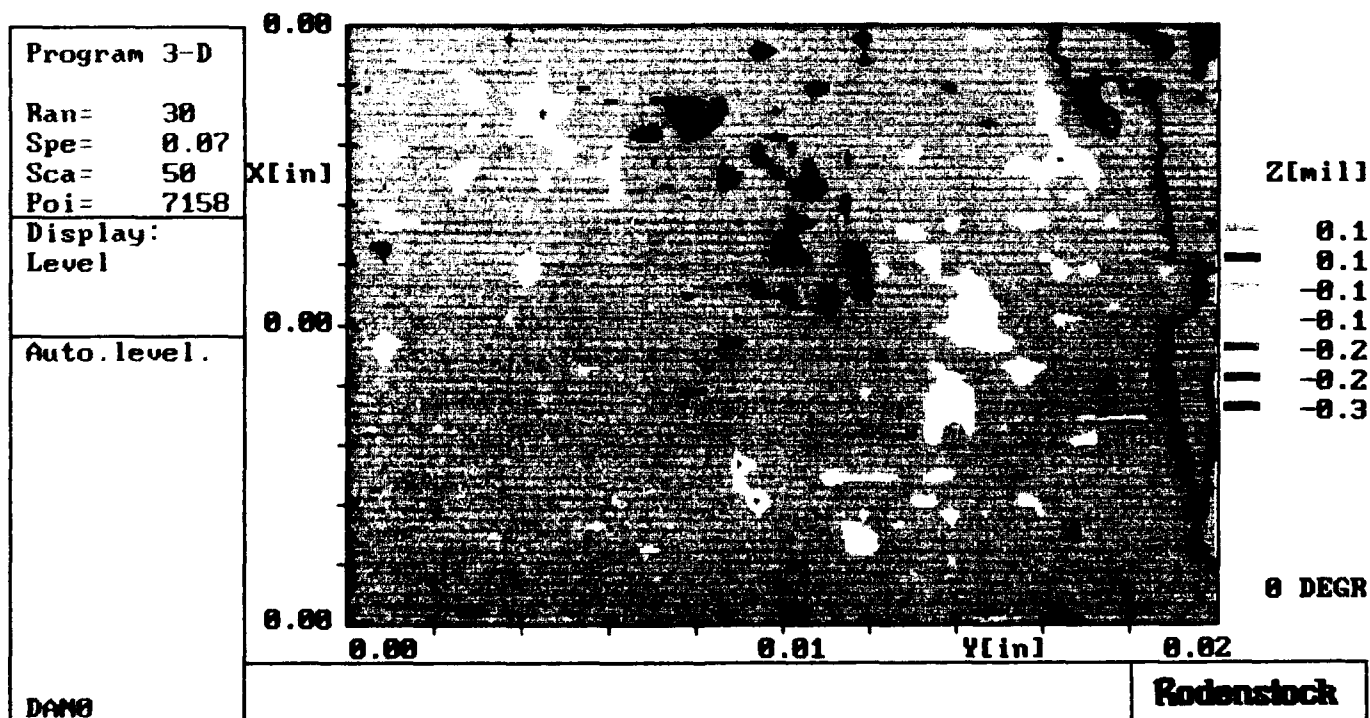


Figure 7. Surface contour of transition zone imaged in previous figure.

REPORT DOCUMENTATION PAGE		1. REPORT NO. FR2198-02	2.	3. Recipient's Accession No.
4. Title and Subtitle FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS Technical Progress Report				5. Report Date 15 December, 1991
7. Author(s) Charles Annis				8. Performing Organization Report No. FR2198-02
9. Performing Organization Name and Address United Technologies Pratt & Whitney P. O. Box 109600 West Palm Beach, FL 33410-9600				10. Project/Task/Work Unit No.
				11. Contract(C) or Grant(G) No. (C) N00014-91-C-0124 (G)
12. Sponsoring Organization Name and Address Office of Naval Research Department of the Navy 800 N. Quincy Street Arlington, VA 22217-5000				13. Type of Report & Period Covered Quarterly 16 Sept - 15 Dec, 1991
				14.
15. Supplementary Notes				
16. Abstract (Limit 200 words) This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences is the major goal of this project.				
17. Document Analysis a. Descriptors Fatigue, Fracture, Single Crystal, PWA 1480, PWA 1484 b. Identifiers/Open-Ended Terms c. COSATI Field/Group				
18. Availability Statement Unlimited		19. Security Class (This Report) Unclassified		21. No. of Pages 12
		20. Security Class (This Page)		22. Price